

Experimental Validation of Graph Theory-Based Leak Detection Algorithm [†]

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Abstract: In this paper, we present results from a study on leak detection based on graph partitioning. Leaks are isolated using graph partitioning and performing mass balances over the partitions. The algorithms are tested and validated using a scaled-down test facility such as the Reconfigurable Testbed for Control and Operation of WDN (RTCOP-WDN). The benefits and limitations of the presented techniques along with the required hardware to test these leak detection methods are discussed.

Keywords: water distribution networks (WDNs); leak detection; graph theory; RTCOP



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1. Introduction

In this paper, we present experimental results from a study on leak detection in a scaled-down test facility. The leaks are isolated using repeated flow balances and valve closures or additional flow measurements [1]. The network is divided into two subnetworks using graph partitioning, and the leak is attributed to a subnetwork based on evidence of the one-sided hypothesis test and flow measurements. This partitioning process is repeated in multiple stages until the leak is identified. Two strategies are used to carry out the flow balances at each stage of the algorithm. In the first method, valves are used to isolate the two subnetworks, whereas in the second method, additional flow measurements are carried out on the edges connecting the two partitions. WDNs are challenging to use to test novel methods since they spread over a large area and have limited infrastructure for measurements and control. Hence, a scaled-down test facility Reconfigurable Testbed for Control and Operation of Water Distribution Network (RTCOP-WDN) is utilized [2]. In this paper, we discuss the pros and cons of two key leak detection techniques along with the associated hardware.

2. Experimental Setup

Four overhead tanks (OHTs) interconnected to twenty demand tanks with distribution pipelines of varying lengths forming four network clusters with five demand nodes each are supplied with water from the reservoir, as shown in Figure 1. It is a highly modular setup supporting different network configurations. Continuous control valves, direct acting solenoid valves, and reverse acting solenoid valves are employed to control the flow of water in the setup. Water level data and flow rates are measured using ultrasonic sensors and Keyence flow sensors, respectively. The NI DAQ devices and Arduino microcontroller are

interfaced between LabVIEW software and the instrumentation system for data acquisition, data logging, monitoring, and control of the network elements.



Figure 1. (a) Three-dimensional model of RTCOP-WDN setup; (b) a fully functional RTCOP-WDN test facility.

3. Methodology

The method of network partitioning followed by hypothesis testing on the flow estimates is repeated in multiple stages until the leak location is identified as depicted in the flowchart in Figure 2a. The two techniques are used to isolate the leak, viz., leak detection by valve isolation and by flow measurement. While the sensor is positioned at the partition in the later approach, the former approach involves isolating a portion of the network. To simulate different leak flow rate scenarios, the network shown in Figure 2b is considered.

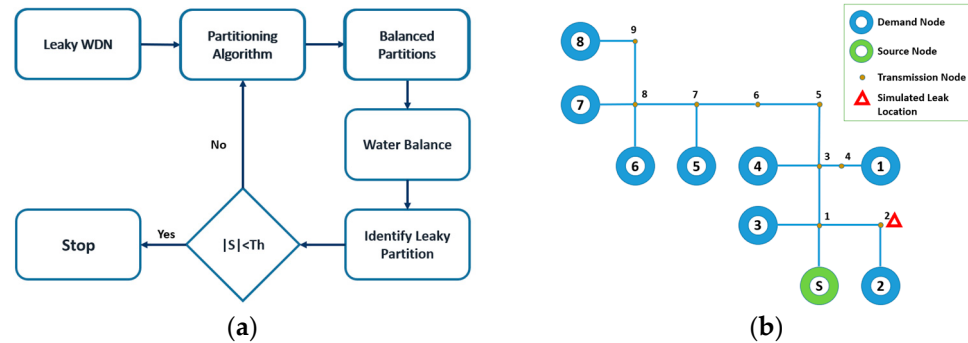


Figure 2. (a) Flowchart of the leak detection process. (b) Test network for leak detection.

The inflow rate (Q_{in}) is estimated from the flow sensor placed in the main pipe, and the outflow rate (ΣQ_{out}) is the weighted estimates of the outflow rates into demand tanks. In the absence of leak, $Q_{in} - \Sigma Q_{out} = 0$, but as the measurements are prone to random errors, they are assumed to be normally distributed with mean $\mu = 0$ and variance σ^2 , where

$$\sigma = \sqrt{(\sigma^2_{Q_{in}} + \Sigma \sigma^2_{Q_{out}})}.$$

But in the presence of a leak, one-sided hypothesis tests are performed and $+3\sigma$ limit is considered in the difference in the flow estimates to detect the presence of leaks as follows,

$$\text{Null Hypothesis } H_0: Q_{in} - \Sigma Q_{out} < 3\sigma \text{ (No leak)} \quad (1)$$

$$\text{Alternate Hypothesis } H_a: Q_{in} - \Sigma Q_{out} > 3\sigma \text{ (Leak)} \quad (2)$$

4. Results

To evaluate the leak detection algorithm's efficacy, leak is simulated at demand node 2 in the RTCOP-WDN setup.

4.1. Leak Detection by Valve Isolation

Using graph partitioning, the network is divided into two subnetworks. The inactive part of the network that receives no water supply is highlighted in an envelope. Flow balance and a hypothesis test on the estimates are carried out in the remaining part of the network to localize the leaks.

Repeated partitioning is carried out from Partition 0 to 4 in Figure 3 until the leak is identified. Using the valve isolation technique, the estimated flow rates from all the partitions and the individual leak status are given below in Table 1.

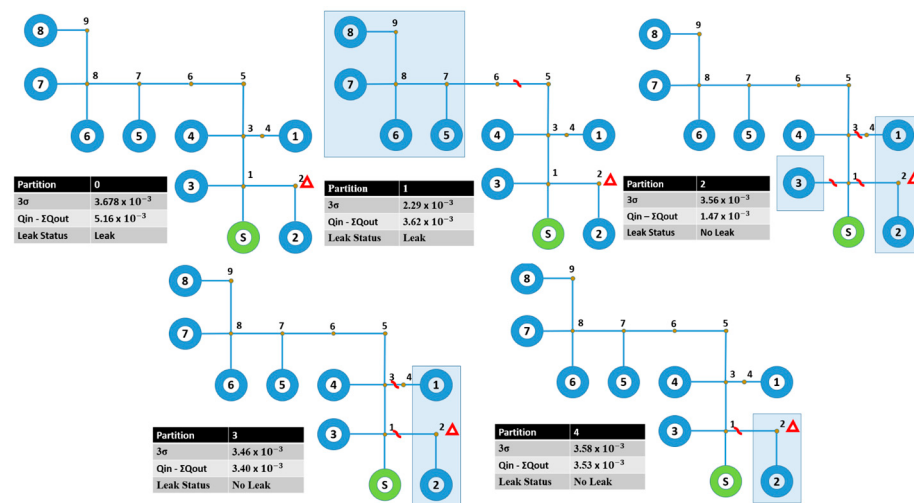


Figure 3. Partition 0 to 4 using leak detection by valve isolation technique.

Table 1. Estimated flow rates and leak status of all the partitions using valve isolation method.

Estimated Flow Rates from All Partitions and Leak Status					
Partition	0	1	2	3	4
Q_{in} (lps)	47.16×10^{-3}	38.12×10^{-3}	23.23×10^{-3}	32.51×10^{-3}	36.75×10^{-3}
ΣQ_{out} (lps)	42.00×10^{-3}	34.50×10^{-3}	22.16×10^{-3}	29.11×10^{-3}	33.22×10^{-3}
$\sigma^2_{Q_{in}}$	1.41×10^{-6}	4.64×10^{-7}	1.24×10^{-6}	1.21×10^{-6}	1.21×10^{-6}
$\sigma^2_{Q_{out}}$	8.98×10^{-8}	1.2085×10^{-7}	1.6677×10^{-7}	1.2643×10^{-7}	2.0953×10^{-7}
3σ (partition)	3.68×10^{-3}	2.29×10^{-3}	3.56×10^{-3}	3.46×10^{-3}	3.58×10^{-3}
$Q_{in} - \Sigma Q_{out}$ (lps)	5.16×10^{-3}	3.62×10^{-3}	1.47×10^{-3}	3.40×10^{-3}	3.53×10^{-3}
Leak Status	Leak	Leak	No Leak	No Leak	No Leak

4.2. Leak Detection by Flow Measurements

Additional flow measurements on the edges connecting the two partitions are used in this method, instead of isolating the partitions. The Keyence flow sensor is attached to the pipe leading to the partition. Thus, no part of the network is inactive in any of the partitions. The part of the network that is connected to the flow meter is highlighted in an envelope. Repeated partitioning is carried out from Partition 0 to 5 in Figure 4 until the leak position is detected. By using the flow sensor technique, the estimated flow rates from all the partitions and the leak status are given below in Table 2.

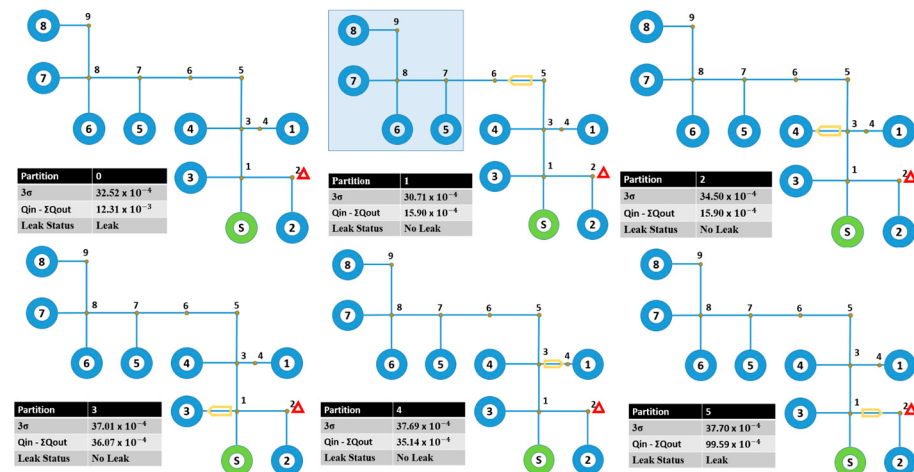


Figure 4. Partition 0 to 5 using leak detection by additional flow measurements.

Table 2. Estimated flow rates and leak status of all the partitions using flow rate sensor method.

Estimated Flow Rates from All Partitions and Leak Status						
Partition	0	1	2	3	4	5
Q _{in} (lps)	51.05 × 10 ⁻³	16.08 × 10 ⁻³	6.65 × 10 ⁻³	10.66 × 10 ⁻³	8.65 × 10 ⁻³	17.13 × 10 ⁻³
ΣQ _{out} (lps)	38.74 × 10 ⁻³	14.49 × 10 ⁻³	4.36 × 10 ⁻³	7.06 × 10 ⁻³	5.14 × 10 ⁻³	7.17 × 10 ⁻³
σ ² _{Q_{in}}	9.28 × 10 ⁻⁷	8.65 × 10 ⁻⁷	3.53 × 10 ⁻⁷	1.33 × 10 ⁻⁶	9.72 × 10 ⁻⁷	1.0129 × 10 ⁻⁶
σ ² _{Q_{out}}	2.48 × 10 ⁻⁷	1.83 × 10 ⁻⁷	9.69 × 10 ⁻⁷	1.92 × 10 ⁻⁷	6.06 × 10 ⁻⁷	5.67 × 10 ⁻⁷
3σ (partition)	32.52 × 10 ⁻⁴	30.71 × 10 ⁻⁴	34.50 × 10 ⁻⁴	37.01 × 10 ⁻⁴	37.69 × 10 ⁻⁴	37.70 × 10 ⁻⁴
Q _{in} - ΣQ _{out}	12.31 × 10 ⁻³	15.90 × 10 ⁻⁴	15.90 × 10 ⁻⁴	36.07 × 10 ⁻⁴	35.14 × 10 ⁻⁴	99.59 × 10 ⁻⁴
Leak Status	Leak	No Leak	No Leak	No Leak	No Leak	Leak

5. Conclusions

In leak detection by the flow measurement method, leaks can be detected in real time without the need to interrupt the supply, unlike leak detection by the valve isolation method. The valve isolation technique accurately pinpoints leak locations due to noticeable flow rate differences. The flow sensor method is particularly useful for identifying minor leaks that do not cause drastic pressure flow rate changes. In practice, a hybrid approach could be considered involving the valve isolation method for the rapid detection of major leaks and flow measurement for detecting gradual leaks that might otherwise go unnoticed. By combining these approaches, WDNs can achieve comprehensive leak detection, minimize water losses, and ensure the sustainable management of water resources.

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Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: Author Sri Hari Prasath R. was employed by the company IITM Pravartak Technologies. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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